Comparison of overhead line lightning performance based on two different tower geometries

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A comparison of the lightning performance of the newly designed Eagle pylon and the traditional Donau pylon, based on tower geometry

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SUMMARY

As a part of reinforcing the 400 kV transmission system in Jutland, Denmark, the Danish TSO is in the process of constructing a new gas insulated substation (GIS) in Revsing. This includes raising a new type of pylon, which will carry the new overhead lines to the GIS. The reliability of the substation and transmission line is of great importance as it is a part of the 400 kV backbone between Sweden, Norway, Germany and the offshore wind farms in Horns Rev, Denmark. The new Eagle pylon has been designed with the focus of minimizing the visual impacted of overhead lines. A detailed lightning performance analysis of the existing Donau and the new Eagle pylon is therefore important in order to assess the risk of failure.
The lightning strike analysis is based on the number of strikes expected to terminate on the line and an investigation of how many of these there may be expected to cause a flashover. The analysis includes an evaluation of both direct stroke and backflashover.
The analysis of direct stroke is performed from calculation of the maximum shielding failure current (I_{MSF}), the shielding failure rate (SFR) and the shielding failure flashover rate (SFFOR).
Backflashover is evaluated using an iterative process recommended by CIGRÉ [4]. The process intends to determine the expected backflashover rate (BFR).
This analysis is performed for both types of pylons and the results compared. From this analysis it is concluded that the phase conductors on the Eagle pylon are significantly better protected from direct stroke than the phase conductors on the Donau pylon. Furthermore with respect to a backflash, the Eagle has a better performance than the Donau pylon.
It is therefore concluded that the Eagle has a better lightning performance than the Donau.

KEYWORDS

Shielding failure rate (SFR), Backflashover rate (BFR), Shielding failure flashover rate SFFOR, Striking distance, Electro geometrical model, Maximum shielding failure current.

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1. METHODS

There are many different methods to analyze lightning performance of pylons. This analysis is based on an Electro-geometrical model (EGM), which in general results in the highest shielding failure current and thereby assumes a worst case scenario, according to [2, p.11]. EGM is also the recommended practice from the IEEE Std. 1243-1997 [3, p.9]. For the analysis of the BFR, the method which is used by the CIGRÉ Working group 33.01 [4] is utilized. Throughout the analysis only the first stroke will be accounted for, thereby neglecting the subsequent strokes.

2. SHIELDING OF OVERHEAD LINES

In order to protect overhead lines (OHL) against lightning ground wires are used. The ground wires are placed on top of the pylons in order to attract the lightning strokes and prevent the lightning from directly terminating on the phase conductors. The geometry and thereby the placing of the ground wires have significant influence on their capability to protect the phase conductors (shielding effects) and in the overall lightning performance of the OHL.
Figure 1 shows both the Donau, which have been widely used in Denmark, and the new Eagle pylon, which is used for the new OHL. It can be seen that the geometry and especially the placing of the ground wires differs significantly between the Donau and the Eagle pylon.

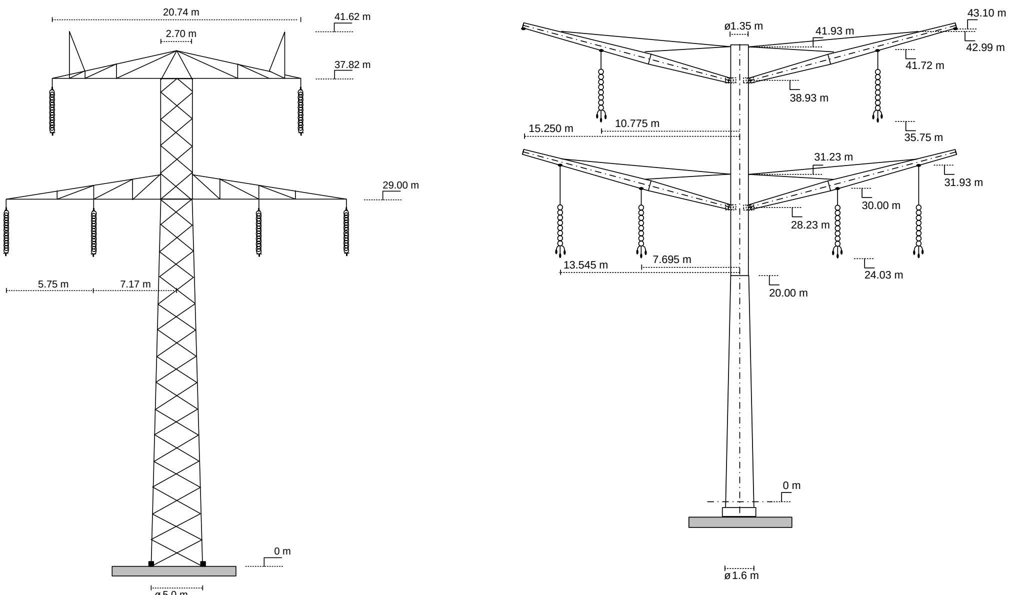


Figure 1 : Eagle pylon on the right side and Donau on the left.

On the Eagle pylon the ground wires are located on the outside of the outer most phase conductor compared to the Donau pylon where two of the phase conductors are placed on the outside of the ground wire.

3. STRIKING DISTANCE

The ground wires do not always protect the conductors from a direct stroke, resulting in shielding failure. When a downwards leader is approaching the OHL from a charged cloud, upwards leaders will be launched from ground wires and phase conductors. If an upwards leader from a ground wire reaches the downwards leader the lightning will terminated on the ground wire. The length of the upwards leader from the conductor is defined as the striking distance. Figure 2 shows the striking distance of an OHL's ground wires and phase conductors [2, p.1].

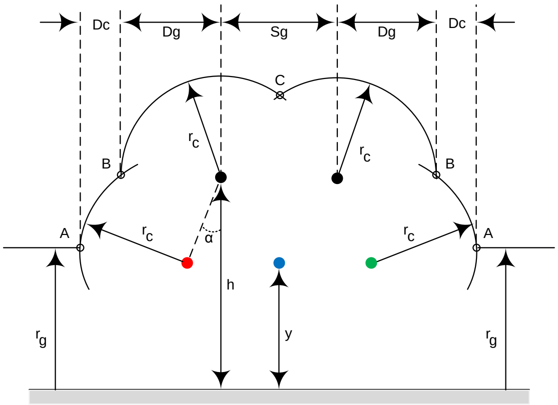


Figure 2 : Illustration of striking distances.

The general equation for striking distance based on the normal electro geometrical model is given in equation 1 [1, p. 249].

$$r_c = AI^B = \gamma \cdot r_g \quad \text{[m] (1)}$$

Where:
r_c is the striking distance of the phase conductor/shielding wire [m].
r_g is the striking distance of the ground, $r_g = \frac{r_c}{\gamma}$ [m].
A, B and γ are constants.
I is the lightning current [kA].

The striking distance may as shown in Figure 2, be represented as the radius r_c of a circle surrounding a conductor. A striking distance to the ground (earth) generated in the same manner also exists. Unlike the circle of a conductor, this is a horizontal line above the ground r_g. If the downwards leader reaches the striking distance in between points A and B shown in Figure 2, the lightning will terminate on the phase conductor. If however the leader reaches the area Dg or Sg the lightning will terminate on the ground wire. Lightning striking outside these areas will terminate on the ground. As the lightning current increases the distance Dc decreases, this is shown in Figure 3.

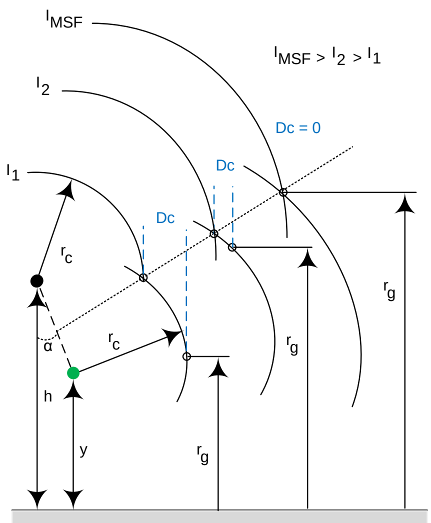


Figure 3 : As the lightning current increases the distance Dc decreases.

The largest current that can terminate on the phase conductor therefore equals the current where Dc=0, this is defined as the maximum shielding failure current (I_{MSF}) which can be determined by equation 2.

$$I_{MSF} = \left[\frac{\gamma \cdot \frac{h+y}{2}}{A(1-\gamma \cdot \sin\alpha)} \right]^{1/B} \qquad \text{[A] (2)}$$

In Figure 3 angle α is defined as positive because the ground wire is placed closer to the center of the tower, than the outer most phase conductor. The shielding angles of the Eagle and the Donau pylons are shown in Table 1, it is seen that the Eagle pylon has a negative shielding angle. This is due to the tower geometry of the Eagle pylon.

Table 1 : Shielding angles of the Eagle and Donau pylons. The angles are with respect to corresponding phase conductors, for the Eagle the lowest one to the right and for the Donau, the highest one.

	Angle [°]
Eagle	-5.11
Donau	14.2

Different values for the constants in equation 1 and equation 2 are given from various sources and standards. Table 2 shows a comparison of how the different sources affect the striking distance and the I_{MSF}.

Table 2 : Evaluation of striking distances using different sources and methods [1].

Electrogeometric models				Eagle Pylon			Donau Pylon		
Source	A	B	γ	r_c [m]	r_g [m]	I_{MSF} [kA]	r_c [m]	r_g [m]	I_{MSF} [kA]
Young	27γ	0,32	γ_y	32,51	30,67	1,49	53,53	50,68	7,16
Brown-Whitehead	7,1	0,75	1,11	33,91	30,55	8,04	57,28	51,60	16,18
Love	10	0,65	1	30,82	30,82	5,65	49,76	49,76	11,81
IEEE-1991 T&D Committee	8	0,65	$1/\beta^a$	33,41	30,58	9,02	91,28	59,95	42,33
IEEE Std. 1243 – 1997	10	0,65	$1/\beta^b$	35,36	30,42	6,98	75,50	56,07	22,42
Wagner & Hileman	14,2	0,42	1	30,82	30,82	6,33	49,76	49,76	19,80
Mousa & IEEE – 1995 Substation Committee	8	0,65	1	30,82	30,82	7,96	49,76	49,76	16,64

Where: $\beta^a = 22/y$, $0,6 < \beta < 0,9$. $\beta^b = 0,36 + 0,17\ln(43 - h)$, if h > 43 then h = 43. y is the phase conductor height. h is the ground wire height. $\gamma_y = 1$ for h < 18 m; 444/(462-h) for h > 18 m

From Table 2 it is seen that the striking distances (r_C, r_G) differs slightly for the Eagle pylon but a lager deviation is seen for the Donau pylon. The different methods show a large difference in the I_{MSF}. It can therefore be seen that the choice of method has large impact on the lightning performance of the pylons.

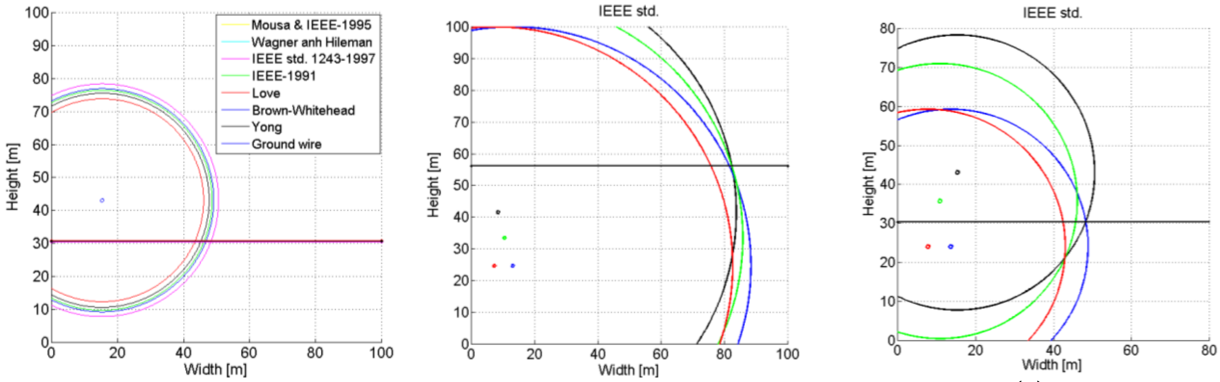
In Figure 4 (a), are shown the striking distances using different methods which result in a deviation of less than 5 meters for the striking distance of the conductor. For the striking distance of the ground, approximately all of the methods result in the same distance.

According to [2, p.11] the IEEE Std. is the one recommended for use. These constants will therefore be used for further evaluation.
The I_{MSF} using the IEEE std. is calculated for the Eagle and Donau pylon respectively and given in Table 3.

Table 3 : Maximum shielding failure current for the pylons.

	I_{MSF} [kA]
Eagle	9.60
Donau	22.42

A plot of the striking distances using the currents from Table 3 for the Eagle and Donau pylons and the constants from IEEE std. is shown in Figure 4.



(a) (b) (c)

Figure 4 : (a) Comparison of striking distance for different sources and standards, (b) striking distance for Donau, (c) striking distance for Eagle.

From Figure 4 it is seen that for I_{MSF} the phase conductors are completely protected by the striking distances from the ground wire and ground.

4. CRITICAL CURRENT

It is furthermore of importance to determine the current needed to cause a flashover of the tower insulators. The critical current (I_C) is the lightning stroke current that will cause a flashover of the insulators. I_C is determined from the characteristic impedance of the line and the critical flashover voltage of the tower insulators and is defined in equation 3 [1, p.249].

$$I_c = \frac{2CFO}{Z_c} \qquad [A]\ (3)$$

Where:
CFO is the critical flashover voltage [V], [IEC60071-2] $CFO = 700 \cdot$ insulator length (3.2 m)
Z_c is the surge impedance of the line [Ω].

The critical currents for the pylons and their respective surge impedances are shown in Table 4.

Table 4 : The critical currents and surge impedances.

	Z_C [Ω]	I_C [kA]
Eagle	252,1	17,80
Donau	241,3	18,57

5. LIGHTNING GROUND FLASH DENSITY

In order to estimate the number of lightning strikes to the transmission line, its shadow area must be analyzed. The grey area beneath the transmission line is called the shadow area, see Figure 5.

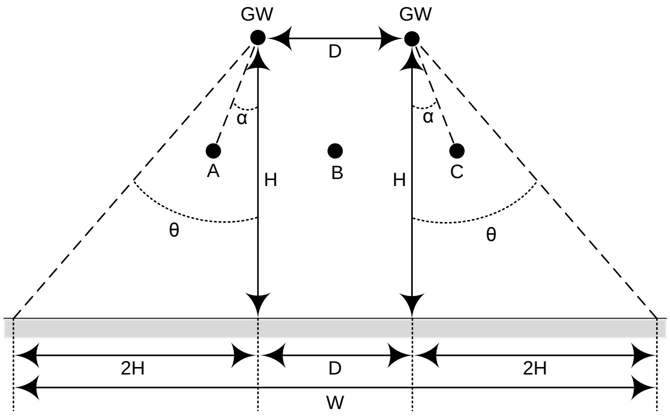


Figure 5 : The shadow area.

If a lightning strikes within this area it is attracted to the line. From the shadow area and the lightning density the expected number of lightning striking the line can be calculated using equation 4 [8].

$$\mathrm{N_{line}} = \frac{N_g}{10} \cdot (28H^{0.6} + D) \qquad [\frac{flashes}{100km \cdot year}] \ (4)$$

Where N_g is the ground flash density and for H and D see Figure 5.

The worst case of ground flash density in Denmark between 2001-2005, was equal to 1.39 flashes/km^2 · year, according to [7]. Table 5 shows the estimated number of strikes to the line using this value.

Table 5 : Estimated number of strikes to the line.

	Flashes per 100km-year
Eagle	38.7
Donau	36.7

From Table 5 it is seen that the Eagle pylon attracts slightly higher number of lightings that the Donau pylon. This is mainly due to larger distance between the ground wires on the Eagle pylon.

6. SHIELDING FAILURE RATE (SFR)

In a previous section the I_{MSF} for both pylons was determined. These are the largest currents that will terminate on the phase conductor. SFR is the number of strokes that will strike the line and a phase conductor, resulting in shielding failure. The SFR is determined by equation 5 [3, p.9].

$$SFR = 2 \cdot N_g \cdot L \int_{3\ kA}^{I_{MSF}} D_c(I) \cdot f(I)_1 dI \qquad \text{[Flashes/year] (5)}$$

Where:
$f(I)_1$ is the probability density function of the first stroke current.
L is the line length [m].
D_C is a function of the stroke current and is given in equation 6 and Figure 6.
Note that the equation only accounts for vertical strokes and the lower bound of the integral is 3 kA, as is recommended by [4, p.24].

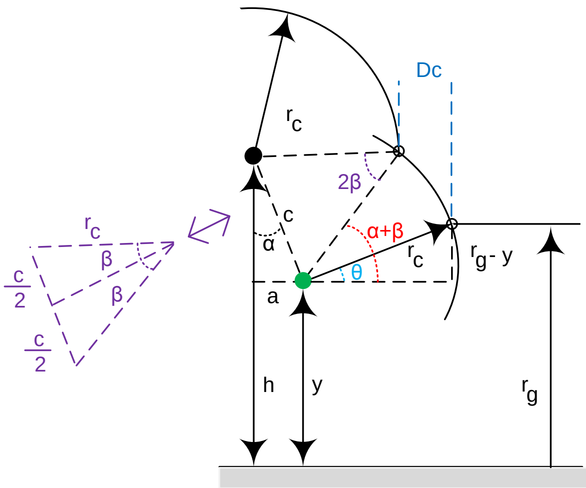


Figure 6 : Dimensions used in equation 6.

$$D_C(\mathrm{I}) = r_c[\cos\left(\sin^{-1}\left(\frac{r_g - y}{r_c}\right)\right) - \cos\left(\tan^{-1}\left(\frac{a}{h-y}\right) + \sin^{-1}\left(\frac{c}{2 \cdot r_c}\right)\right)] \qquad \text{[m] (6)}$$

Furthermore in order to calculate the SFR the probability density function $f(I)_1$ of the first stroke current is needed. According to [4, p11] the log-normal distribution for the first stroke amplitude can be calculated as shown in equation 7.

$$f(I)_1 = \frac{1}{\sqrt{2 \cdot \pi} \cdot \beta \cdot I} \cdot e^{-\frac{1}{2}(z)^2} \qquad \text{[-] (7)}$$

Where:
$z = ln(I/M) / \beta$
β is the logarithmic standard deviation, see Table 6.
M is the median value of the striking current, see Table 6.

Table 6 : Constants used in equation 7 [4, p13].

Parameter	Shielding failure domain (I < 20 kA)	Backflash domain (I < 20 kA)
M	61	33.3
β	1.33	0.605

The calculated SFR values for both pylons are given in Table 7.

Table 7 : SFR results for the pylons.

	SFR [flashes/year]
Eagle	0.0353
Donau	0.1150

As can be seen from Table 7, there is a relatively large difference between the SFR for the Eagle and the Donau pylon. This is in line with the maximum shielding failure current for the Donau being higher than for the Eagle.

7. SHIELDING FAILURE FLASHOVER RATE (SFFOR)

SFR may however not mean that all of these strokes will result in a flashover. In this section the SFFOR is determined. This is the number of lightning strikes to the phase conductor that will result in a flashover of the insulation. This rate may be calculated using the same expression as for the SFR, but now integrating from I_C to I_{MSF}, this is shown in equation 8 [1, p.250].

$$SFFOR = 2 \cdot N_g \cdot L \int_{\mathrm{I_c}}^{I_{MSF}} D_c(I) \cdot f(I)_1 dI \qquad \text{[Flashes/year] (8)}$$

I_{MSF} and I_C for both types of pylons have earlier been determined and are shown in Table 8, for convenience.

Table 8 : The critical and maximum shielding failure currents.

	I_C [kA]	I_{MSF} [kA]
Eagle	17,80	9.61
Donau	18,57	22.42

For the Eagle pylon it can be seen that I_C is larger than I_{MSF}. Therefore, theoretically no lightning current can strike the phase conductor and create a flashover. From this it can be concluded that the theoretical SFFOR for the Eagle pylon is zero.

This is however only a theoretical assumption as according to IEEE [3] there is an 8 % change that the first stroke is below 12 kA. This means that there is some change that the first stroke is below the I_{MSF} value, thereby striking the conductor. If the first stroke is followed by a subsequent stroke, the subsequent stroke will follow the same leader as the first stroke. The subsequent stroke may be higher than the *Ic* and result in a flashover. IEEE suggest a method to account for this possibility however this will not be further considered in this study, due to the recommendations in [1, p.267]. However it should be kept in mind that flashover can occur from subsequent strokes.

For the Donau pylon the I_{MSF} exceeds the I_C. Therefore there is a chance that the lightning strikes a phase conductor on the Donau pylon and creates a flashover to the tower. The SFFOR is calculated and the result is shown in Table 9.

Table 9 : The SFFOR results for the Eagle and the Donau.

	SFFOR [flashes/year]
Eagle	0
Donau	0.0234

The SFR and the SFFOR were determined for the Eagle and the Donau pylon in the previous sections.

From this it is seen in regard to SFR and SFFOR that the Eagle pylon performs better than the Donau pylon, due to tower geometry and negative shielding angle of the Eagle pylon.

8. BACKFLASHOVER RATE (BFR)

In the event of a strike to the ground wire or the tower, a current is forced down the pylon and divided between a current entering ground through tower and another current divided into two which are entering the ground wires in each direction. As a result, voltage will build up across the insulators as the potential of the pylon rises compared to the phase voltage. If the potential of a tower rises to a value where the insulator string no longer can withstand the voltages between the tower and the phase conductor, a backflash can occur.

The method used in this analysis is the method proposed by CIGRÉ [4, p.40-48] (see flowchart in Figure 7) and [1, p.396].

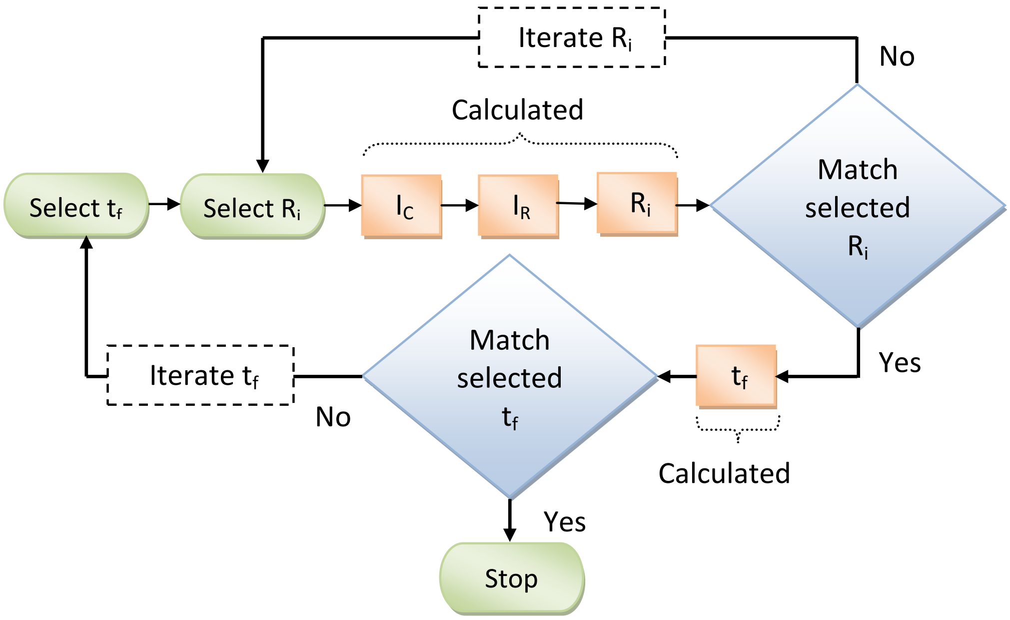


Figure 7 : Flowchart of the CIGRE method for determining the impulse resistance R_i and the time to crest t_f.

The calculation of the BFR is an iterative process for which the procedure is given below. The equation for calculating the BFR is as shown in equation 9.

$$BFR = 0.6 \cdot N_{line} \int_{Ic}^{\infty} f(\mathrm{I}) dI \qquad \left[\frac{Flashovers}{100km-year}\right] \quad (9)$$

Where:
f (I) is the probability density function of stroke current.

The upper limit of the integral is 200 kA in accordance with [4].
According to [1, p.379] the voltage produced by a stroke to the span will always be equal or less than the voltage produced by a strike to the tower. It is therefore recommended to only assume strikes to the tower, when calculating the BFR. This rate will however be too high if strikes to the span are not considered and therefore BFR must be multiplied by 0.6 [1, p.379].

To evaluate equation 9 the lower integration limit must be determined, this is done in the followings steps and values used are shown in Table 10 :

1. Select the value for the impulse resistance R_i, typical first guess is $0.5 \cdot R_0$ [1, p.397].
2. Select time to crest t_f [μs], typical value of 4, for 354 kV and above [1, p.397] .
3. Calculate the couplings factor between ground wire and phase A: C_a [1, eq:4.41].
4. Calculate the couplings factor between ground wire and phase B: C_b [1, eq:4.41].
5. Calculate the couplings factor between ground wire and phase C: C_c [1, eq:4.41].
6. Determine the lowest couplings factor.
7. Calculate the non-standard CFO [1, eq:4.51].
8. Calculate the critical current I_C [1, eq:4.57].
9. Calculate the grounding current I_R [1, eq:4.16.]
10. Recalculate R_i [1, eq:4.20].
11. Compare the initial calculated R_i with the value of R_i calculated in number 10, if the two values are within a specified limit stop, otherwise iterate (replace initial value with calculated value).
12. When step 11 converges, recalculate $t_f = 0.207 \cdot I_C^{0.53}$.
13. Compare the initial selected t_f with the value of t_f calculated in number 12, if the two values are within a specified limit stop, otherwise iterate (replace initial value with calculated value).
14. When step 13 converges, the value I_C, is the lower limit in equation 9.

Table 10 shows that the current needed for a backflashover is very high, relative to the normally used upper limit of 200 kA [4]. This result in an almost zero possibility of a flashover, which is somewhat questionable.

Table 10 : Results from BFR iteration process for earth resistivity of 100 Ω·m.

Value [Unit]	Eagle	Donau
Z_T [Ω]	239.93	203.19
Z_g [Ω]	332.13	352.44
Span [m]	300	300
R_i [Ω] (initial)	5	5
t_f [μs] (initial)	4	4
C_a	0.2388	0.2333
C_b	0.1283	0.1486
C_c	0.1350	0.1425
CFO_{NS} [kV]	2611	2227
I_C [kA]	422	366
I_R [kA]	413	362
R_i [Ω]	3.66	3.94
t_f [μs]	5.1	4.76
BFR [flashover/100km·year]	0.000313	0.000812

There are several factors which may introduce errors, which are difficult to correct without further testing. These factors are:

- The exact value of the grounding resistance $R_{i.}$
- The precise value of the ground resistivity. According to [5, p.31] the soil in Denmark has a lot of sand and clay. The resistivity for clay and sand is 100 and 150 Ω·m respectively. Suggesting a value in-between the two.
- The exact value of the CFO. There exist numerous methods to calculate the CFO and the exact value of this may vary from the one calculated in this paper.

It is therefore of interest to perform a sensitivity analysis of these parameters. Shown in Table 11 are the critical current and the BFR for different value of the fore mentioned factors. The base values used are the ones from Table 10 for Eagle.

Table 11 : The critical current and BFR for typical values.

Pylon :	Eagle	I_C [kA]	BFR [flashover/100km·year]
R_0	10 Ω	258.9	0.0081
	25 Ω	182	0.0585
	50 Ω	169.43	0.1043
CFO	1425 kV	139.64	0.2102
	1600 kV	163.47	0.0992
	2240 kV	258.9	0.0081
Soil resistivity	100 Ω·m	422	0.0003
	600 Ω·m	258.9	0.0081
	1000 Ω·m	242.14	0.1257

It is apparent that the BFR is very dependent on each of the parameters. This indicates that the method is very dependent on the input parameters. It may be recommended to assure as low as possible grounding resistance of the pylons closest to the substations.

9. CONCLUSION

The results for the SFR, SFFOR and BFR are combined in Table 12.

Table 12 : Results from the SFR, SFFOR and BFR analysis.

	SFR [flashes/year]	SFFOR [flashes/year]	BFR [flashover/100km·year]
Eagle	0.0353	0	0.000313
Donau	0.1150	0.0234	0.000812

It is evident from Table 12, that the Eagle pylons lightning performance is better than the Donau pylon.

In the case of direct strokes, both the SFR and SFFOR result in a lower rate for the Eagle pylon than for the Donau. This is due to the geometry of the two pylons especially the fact that the Eagle pylon has a negative shielding angle.

In the case of the BFR the geometry of the pylons results in different coupling factors, which account for the difference of the two pylons.

A comparisons of the maximum shielding failure revealed that the current which will strike the phase conductor directly is lower for the Eagle than it is for the Donau. As a result, the voltage which will appear at the substation terminals will be higher for the Donau, and thereby increase the stress on the substation components.

The new Eagle pylon (shown in Figure 8) is, besides having a more elegant design, a better technical solution in regard to lightning performance.

Figure 8 : A picture of the Eagle and the Donau pylons.

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